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Estimating carbon stocks in young moraine soils affected by erosion

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ABSTRACT

In this paper the storage potential of soils within a heterogeneous structured hummocky young moraine region for organic carbon is discussed with respect to climate change and erosion. Erosion is discussed to be either a global terrestrial CO_2 sink or a source. In hummocky young moraine regions of North East Germany water and tillage erosion are steadily changing factors since the beginning of arable landuse in ancient times. For such topographically complex landscapes the knowledge on soil organic carbon (SOC) dynamics and the limits of carbon storage are still limited. Our objective is to combine data collected during former soil erosion studies with recent findings on (i) soil property and (ii) estimated "optimal" SOC data to predict the SOC storage related to tillage and crop rotation, among others. Classified catenae were analysed for texture, SOC, CO_3-C, nutrient contents, and depth of weathering. Optimal SOC contents were estimated on the fine sized particle content. Arable soil at convex slope positions of steep catenae show 4 time smaller SOC stocks as compared to respective forest soils and to arable soils at concave position. Our findings suggest changes in SOC stocks to be almost exclusively related to decomposable carbon pools. Comparison of estimated optimal with measured SOC contents in soils at such positions indicated that such soils could potentially store a surplus of 0.6 to 0.8 g kg^{-1}. SOC protection at convex positions is limited by soil texture, and frequent truncation of the respective soil profiles. Whereas truncation followed by downhill transfer may bury SOC at sedimentation/concave positions resulting in long-term SOC storage as far as decomposition is prevented by site conditions.

1. Introduction

Soil and climate are connected by complex interactions. The increase in carbon dioxide concentration of the atmosphere is discussed to affect the world's climate (IPCC, 2014). Climate-relevant gases (e.g., CO_2, N_2O and CH_4) were exchanged by complex processes between soils and atmosphere. In soils approximately $1500 \cdot 10^9$ Mg C is stored within the soil organic matter. This is about three times the amount of carbon stored in the entire biomass (Bodenatlas, 2015; MPG, 2016) in consequence soils offer the most important carbon sink. However, soils may act also as a source for carbon dioxide, and the quantities of carbon stored in soil differ significantly between various soils and climate zones: For terrestrial soils the storage capacities are smaller than that of semi-terrestrial soils (e.g., gley, marsh, alluvial soils). For groundwater influenced soils it is higher than for drained soils (Blume et al., 2010; Rinklebe, 2004) and it decreases in the sequence forest > grassland > arable land (e.g., Guo and Gifford, 2002; Freibauer et al., 2004; Smith, 2004; Leifeld and Kögel-Knabner, 2005). Determining SOC storage in soils as a climate protection effort is often difficult since geographic and temporal conditions are highly variable and changes in SOC mostly need decades to reach a new equilibrium (Hülsbergen and Rahmann, 2013; Körschens et al., 2014; Powlson et al., 1996). However, Körschens (1980) found by investigating soils with > 50 years of bare fallow the amount of inert organic carbon (i.e. the proportion of remaining SOC) generally to be related to the content of fine sized mineral soil particles (< 63 µm, cfs). Körschens et al. (2014) and Isermann and Isermann (2011) assume the cfs content to determine a lower and upper limit for the C storage potential in arable soils.

Since the Atlantic period (ca. 8000 BCE) the intensity of arable land use has globally increased and water erosion accelerates. Soil erosion is associated with carbon and nutrient fluxes (Quinton et al., 2010). For the past 4500 years Bork et al. (1998, p. 103) estimated for different time scales the following losses of soil masses and carbon based on the thickness of sediment layers (Table 1). These findings indicate that C loss caused by arable land use is about 20 times (270 kg C ha^{-1} y^{-1}) higher at the beginning of the 20th century as compared to that in the Bronze Age (14 kg C ha^{-1} y^{-1}). Consequently erosion is regarded as one of the most important threats to soils fertility (e.g., Montanarella et al., 2016; Pimental, 2006; Lal, 2005; Gregorich et al., 1998). The potential amount of sediment annually transferred by water erosion was estimated between 35,000 Tg y^{-1} (Quinton et al., 2010), 130,000 Tg y^{-1} (Reich et al., 2001) and 200,000 Tg y^{-1} (Lal, 2003).

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Table 1
Estimated soil and soil organic carbon (SOC) within time spans between 800 and 100 CE, 100 CE to 1910 and 1910 to 1988 (in brackets SOC contents assumed for translocated sediments).

Time scale	Soil loss Mg ha^{-1} y^{-1}	Carbon loss kg C ha^{-1} y^{-1}
800 BCE to 100 CE (Bronze Age and Iron Age)	6.1	14 (0.2%)
100 CE to 1910 (Middle Ages and Modern Age)	8.4	34 (0.4%)
1911 to 1988 (Modern Age)	33	270 (0.8%)

Such sediment transfer rates caused by water erosion will result in annual carbon (C) transfer rates of approximately 500 ± 150 Tg globally. However, the annual carbon transfer rates into river systems and oceans calculated by Quinton et al. (2010) are much lower (80 ± 20 Tg C).

Erosion may cause a burial of SOC at concave positions resulting colluvial soils to act as sinks for organic carbon. However, conditions of precipitation (intensity, duration), site (landuse, cover crop, soil conditions) as well as topography are known to affect kind and amount of eroded material (Richter, 1998). Such that colluvial soil will only act as a sink for SOC if the buried SOC remains stable, but may act as a source for CO_2 if SOC decomposition occurs (Kleber et al., 2015; Lorenz and Lal, 2012). Additionally at steep slopes a selective transport of particle size classes (Hjulström, 1935) may cause event specific textural rearrangements at the burial sites. Fine sized particles may -due to their small specific weight- potentially be translocated straight forward into drainage systems, while coarser sized particles will mostly remain at footslope positions (e.g., Doetterl et al., 2016). This is validated by Herzog (1990) who found by replacing Ap horizons by subsoil for the initial 7 year period a SOC sequestration, that increases until the 14th year after application (Herzog and Kunze, 1976), and then approached 90% of the site-specific SOC concentration determined by texture. However, Herzog and Kunze (1976) found the burying of SOC-rich soil to provide a possibility for permanent SOC storage which is confirmed by Müller (1980).

Assumptions whether erosion may act as a global terrestrial CO_2 sink or source remains still open (e.g., Lal, 2005) since different authors present contradictory estimations: Stallard (1998) and Ito (2007) estimates soil to be strong sinks (1000 to 2000 Tg y^{-1}), while van Oost et al. (2007) estimates them to be weak (by 400 Tg y^{-1}), and Lal (2003) assumed them to be strong sources (4000 to 6000 Tg y^{-1}). For understanding of landscape-scale SOC dynamics in cropland soils knowledge on effects of erosion on SOC dynamics becomes important (e.g., Quine and van Oost, 2007). The knowledge of SOC dynamics and the limits of carbon storage potential in erosion influenced arable soils in topographically complex landscapes are still limited (e.g., van Oost et al., 2007).

"*Long-term*" studies on soil erosion, starting originally in the 1980th for estimating soil erodibility in a hummocky young moraine region (Frielinghaus et al., 2002) offer a possibility for estimating erosion effects on the SOC storage potential of soils within time spans between 10 and 20 years related to site conditions, tillage, crop rotation among others.

Our objectives are to combine data collected during such "*long-term*" studies on erosion events together with actual soil property data to

(i) determine erosion driven effects on carbon storage potential of soils from a young moraine region with respect to
   a. land-use
   b. slope steepness and -position
(ii) differentiate the effect of tillage on SOC storage from the effect of water erosion
(iii) discuss the storage potential of arable soils for surplus carbon by comparing the erosion driven storage potential with the one estimated from the contents of fine sized mineral soil particles (< 63 µm, cfs), according to Körschens (1980).

2. Materials and methods

2.1. Study area

The studied sites located in Mecklenburg and Brandenburg are typical for a hummocky ground moraine landscape. The land forming processes during the glacial periods (i.e., Pommeranian stage; 15,200 years ago (Liedtke, 2003)) contributed to characteristic landscape properties of the soil formation: a relatively thick ground moraine and a strong differentiation of relief and typical thickness of Bt horizons. Eroded material is mostly deposited in lower parts of the catchment: concave positions, such as small depressions, kettle holes, or ponds. Processes of erosion and deposition caused a highly heterogeneous landscape (Schmidt, 1997) with Calcaric Regosols (truncated soil profiles), slightly eroded Luvisols - on convex and mid slope positions, respectively-, and Colluvic Regosols at concave positions. The concave positions often show deep colluvial deposits with Gley or Pseudogley characteristics (Schatz, 2000).

2.2. Studied sites

We compared erosion effect on SOC content for soils different in (A) land use (neighboured forest and grassland catenae), (B) slope steepness and catenae position, (C) tillage and site conditions – and (D) longer-term (10–20 years) tillage and crop rotation.

Slope and soil type were classified according to KA5 (AG Boden, 2005; IUSS, 2007). All investigated catenae were classified by considering inclination, morphology, horizon sequences, and soil types. Soil characteristics such as texture, SOC, CO_3-C, nutrient contents, depth of weathering were categorised according to Schmidt (1986) (Fig. 2).

2.2.1. A – Land use (neighboured forest and grassland catenae)

Near the city of Burg Stargard (Fig. 1, Table 2) neighboured catenae (type IV) under forest and under grassland with similar slope steepness were sampled (Frielinghaus and Ellerbrock, 2000). At the forest site well-developed Ael-horizon depleted in clay content and distinct illuviated Bt-horizons were formed above the C horizon with decalcification reaching down to 135 cm depth (Table 4). On today's grassland, a) Calcaric Regosols developed during the 250 years after deforestation caused by erosion at the concave positions and b) Colluvic Regosols due to continuous sedimentation processes at the convex positions.

2.2.2. B – Slope steepness and catenae position

According to Schmidt et al. (1986, Fig. 2) classified arable sites different in slope steepness were chosen that are located north and south of the terminal moraine of the Brandenburg stage in the hummocky young moraine (Table 2). Soils from flat catenae (Slope-steepness: 4 to 12%) were sampled at Müncheberg, Deven, Prötzel and Malchin site. While soils from steep catenae (Slope steepness: 8 to 18%) were sampled in Holzendorf and Brüel site (Fig. 1). The ANOVA single factor of "Excel's Analysis ToolPak add-in" was used for statistical analysis (Microsoft, 2014).

2.2.3. C – Tillage and site conditions

The effects of different tillage techniques (e.g., plough, cultivator and disc harrow) on erosion were studied at a field experimental site (Müncheberg; Kietzer, 2007) and at field sites located near Prenzlau (Augustenfelde, Basedow, and Holzendorf; Table 2). The soils ^{137}Cs-inventory was used as a tracer to distinguish effects of water erosion from that of tillage erosion throughout the past decades (Li et al., 1999; Lobb et al., 1995).

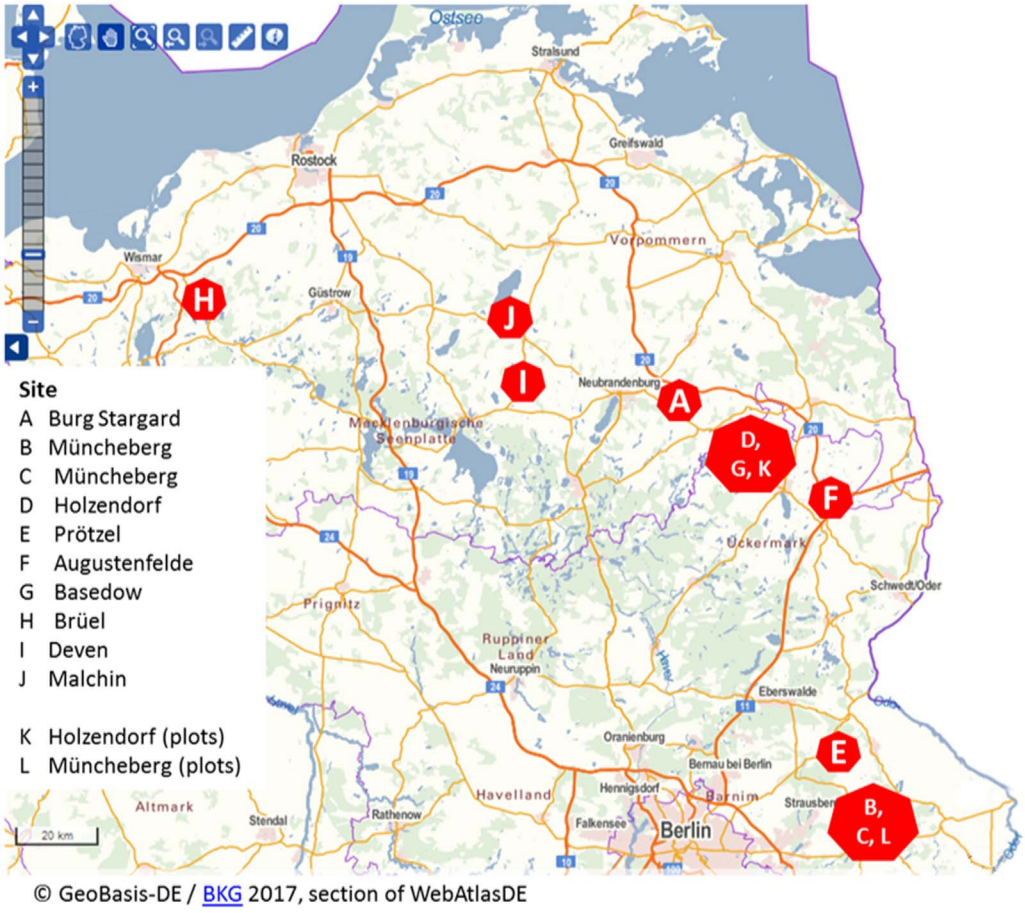

Fig. 1. Map with the location of the investigated sites (for letters see Table 2).

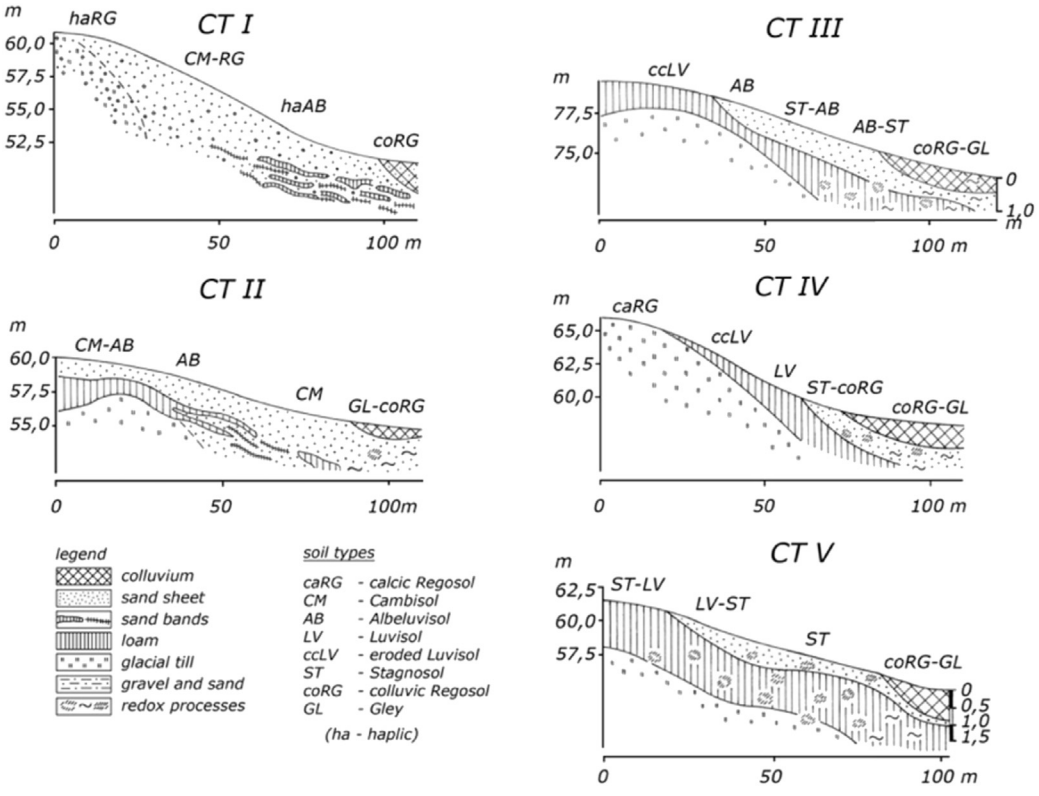

Fig. 2. Catenae classified according to Schmidt (1986).

Table 2
Location, soil type, land use and slope steepness of the investigated sites.

Site	Location (lat/lon)	Letter in Fig. 2	Soil type (IUSS, 2007)	Characteristic of land use	Slope steepness catenae type
Burg Stargard MV	53.502272. 13.437533 53.499931. 13.437533	A	Brunic Arenosol Calcic Luvisol/Haplic Regosol	Forest Cropland	Steep CT IV
Müncheberg BB	52.515304. 14.127143	B	Cambic Albeluvisol	cropland	Flat CT II
Müncheberg Bäckerweg	52.527465. 14.100858	C	Haplic Regosol	Cropland	Flat CT II
Holzendorf BB	53.385371. 13.791150	D	Haplic Regosol	Cropland	Steep CT IV
Prötzel BB	52.659296. 14.007752	E	Haplic Albeluvisol Cambic Albeluvisol	Cropland	Flat CT II
Augustenfelde BB	53.278579. 13.908742	F	Calcic Luvisol/Haplic Regosol	Cropland	Flat CT III
Basedow BB	53.34669. 13.77770	G	Calcic Regosol Cambic Albeluvisol	Cropland	Steep CTI
Brüel MV	53.740670.11.682224	H	Brunic Arenosol/Calcic Luvisol	Cropland	Steep CT IV
Deven MV	53.561764. 12.862936	I	Calcic Luvisol	Cropland	Flat CT III
Malchin MV	53.713566. 12.816131	J	Luvic Stagnosol/Calcic Luvisol	Cropland	Flat CT V
Plot station					
Holzendorf BB	53.386818. 13.780225	K	Haplic Regosol/Calcic Luvisol	15 plots with 5 different plants	Steep CTIV
Müncheberg BB	52.515607. 14.128106	L	Cambic Albeluvisol	7 long plots, crop rotation, catenae exploration, tillage experiment	Flat CT II

2.2.4. D – Longer-term (10–20 years) tillage and crop rotation

In 1980th a field experiment at Holzendorf site with 15 standard measurement plots (20 m by 2.5 m) were established at mid slope positions according to Wischmeier and Smith (1978) in three replicates (n = 3). Five variants of crop rotations with soil covers ranging from bare fallow to perennial grassland were examined to adopt the Universal Soil Loss Equation (USLE) for the respective site conditions (Tables 2, 3). From the years 1982 to 1997 five soil samples per plot (centre, within 4 m distance) were taken annually in March from Ap horizon (5–20 cm depth) to obtain one mixed soil sample.

In 1990 to 2005 further soil erosion measurements were started at Müncheberg experimental field (ZALF-test sites) to analyse the combined effects of soil tillage and crop rotation. Seven plots of 53 m length by 6 m width with different crop rotation and soil tillage were established. At this ZALF test site since 2006 the experiment is continued with two plots of 53 by 9 m size, and two tillage systems for energy crops (a conventional one with ploughing, and a no-till) (inclination 6%, weak silty sand). At both plots soil loss, runoff and nutrient transport were measured and analysed regularly after heavy rainfall events during the years 2006 to 2016 (with 7 (2015) and 24 measurements per year in 2007). During erosion events time dependent samples of sediments and run-off were taken using a cascaded system consisting of a barrier, a venturi (V)-channel, a time scheduled sampler, and a further collection tank behind a slot sampler (Coshocton-wheel). In this system a flow velocity dependent distribution of sediment sampling of coarse and fine sized material is recorded. The SOC content of the eroded solid material was analysed (Deumlich et al., 2017).

Table 3
Crop rotations at Dedelow long-term field experiment.

Variant[a]	1982–1986	1987–1997
1	Winter rye (WR)	
2	Corn with narrow rows (35 cm)	Rotation (WR with undersown crop (*Dactylis glomerata*. docksfoot). Corn 70
3	Corn normal row width (70 cm. Corn 70)	
4	Corn with 50 cm row distance	Alfalfa/clover/grass
5	Continuous fallow	

[a] Between 1994 and 1997 only one plot per variant was cultivated.

2.3. Analysis of soil properties

The mixed soil samples and the solid samples from the erosion events were air dried, and sieved to pass 2 mm. For the soil samples the particle size distribution was analysed by wet-sieving and sink velocity after organic matter destruction with H_2O_2 and chemical dispersion using $Na_4P_2O_7$ (DIN 11277, 2002). Organic C content (SOC) was determined according to DIN ISO 10694 (1996): the total carbon content is analysed by elemental analysis after dry combustion as carbon dioxide via infrared detection after dry combustion at 1250 °C in duplicate (LECO; Mönchengladbach) according to DIN ISO 10694 (1996). The carbonate carbon content was determined by gas chromatographic analysis of carbon dioxide evolution after application of phosphoric acid using a Woesthoff apparatus according to DIN ISO 10693 (1997). Both measurements were done in two replicates. The content of soil organic carbon (SOC) is calculated from the difference between total carbon and carbonate content (DIN ISO 10694, 1996). The detection limits are 0.1 g kg^{-1} for SOC.

The samples from Augustenfelde, Basedow, and Holzendorf sites were analysed for the specific ^{137}Cs-activities according to Walling and He (1998). Measurement was done using a GMX detector by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, Federal Office for Radiation Protection (BfS; Berlin). A comparison based on the mass balance model 3 (MBM3) of Walling and He (1998) between a none erosion affected grassland area (control) and an erosion affected arable slope is used to distinguish the rate of water from that of tillage erosion.

2.4. Estimating the maximum SOC storage capacity by the content of fine sized mineral particles

Körschens (1980) suggested estimating the content of inert SOC by

Table 4
Depths, bulk density, pH, contents of fine sized mineral particles (< 63 µm; cfs), total carbon (TC), carbonate-carbon (CO_3-C), nitrogen (Nt), soil organic carbon (SOC) and SOC stocks of soil from different horizons in soil profiles at convex and concave positions under grassland, and forest at Burg Stargard site.

			Depth [cm]										
		Horizon	Upper	Lower	BD	pH	cfs	TC	CO_3-C	Nt	SOC	SOC mass of whole profile	Rel. to forest
					Mg m^{-3}		%	g kg^{-1}			g kg^{-1}	kg m^{-2}	%
Convex slope	Forest	Ah	0	10	1.3	3.8	16.5	30.4	0	1.68	30.4	10.4	100
		Ah/Ael	10	25	1.45	3.5	17.8	9.7	0	0.63	9.7		
		Ael	25	45	1.45	3.6	18.5	3.75	0	0.24	3.75		
		Btg	45	95	1.58	4.4	27.2	2.36	0	0.21	2.36		
		Cv	95	135	1.65	4.8	35.8	2.1	0	0.27	2.1		
		Cc	< 135		1.65	6.6	22	7.3	5.5	0.21	1.8		
	Grassland	Ap	0	20	1.52	7.3	13.6	12.1	4.27	1.1	7.81[a]	2.4	23
		Cv	20	50	1.65	7.3	18.8	21.5	16.8	0.2	4,7		
		Cc	50	150	1.65	7.2	19.4	18.3	17.6	0.14	0.7		
Concave slope	Forest	Ah	0	15	1.3	3.5	10.2	19.9	0	1.08	19.9	8.8	100
		Ah/Ael	15	30	1.45	3.6	13.1	7.37	0	0.45	7.37		
		Ael	30	65	1.45	4.1	13.8	3.35	0	0.21	3.35		
		Btg	65	110	1.58	4.6	25.7	1.6	0.2	0.21	1.4		
		Cv	110	150	1.65	4.2	26.9	1.07	0.1	0.12	0.97		
	Grassland	Ap	0	25	1.52	5.5	15.8	10.7	0.2	0.96	10.5[b]	9.7	110
		wM	25	75	1.58	6.6	15.9	6.2	0.2	0.6	6		
		Ael	75	105	1.65	6.6	12.3	0.5	0.1	0.12	0.4		
		Btg	105	135	1.65	6.3	48.8	1.6	0	0.3	1.6		

[a] SOC_{opt} = 8.4 g kg^{-1}.
[b] SOC_{opt} = 9.3 g kg^{-1}.

the content of fine sized mineral particles (< 63 µm, cfs[1]) for arable soils at plane landscapes as follows:

$$SOC \geq cfs * 0.04 + 0.3 \text{ (at least 0.6; valid for plain position) in\%} \quad (1)$$

This equation is used here as a measure for maximum ability of arable/grassland soils at convex positions to store SOC (upper limit for SOC storage potential) (Körschens et al., 2014; Isermann and Isermann, 2011).

3. Results

3.1. Land use (neighboured forest and grassland catenae)

For Burg Stargard (type IV) under forest independently on the slope position Haplic Luvisols were found with SOC contents between 20 and 30 g kg^{-1}. For the today's grassland soils (arable land with ploughing until 1992) the SOC contents at convex slope positions (7.8 g kg^{-1}; Calcaric Regosol) of steep catenae were found to be 1.3 times smaller as compared to that of concave position (10.5 g kg^{-1}; Colluvic Regosol) and to be about 4 times smaller than that of forest soils at convex position (30.4 g kg^{-1}; Haplic Luvisol). However, the SOC stocks of the whole profile (Ap down to the Cc horizon) is for the soil from the arable convex position (2.4 g kg^{-1}) about 4 times lower than that at the concave position (9.7 g kg^{-1}; Table 4). Such contents are in the ranges of mean SOC contents for arable soils at this hummocky young moraine sites (Kundler, 1989).

The SOC stocks of forest soils (i.e., calculated for a depth down to the Cc Horizon; Table 4) at convex positions were found - in accordance with the literature (Blume et al., 2010; Leifeld and Kögel-Knabner, 2005; Thiere et al., 2005) - to be about 34% higher as compared to that of the grassland soils. In contrast the SOC-stocks of the soils at the concave positions are similar for arable and forest site (88 to 97 Mg ha^{-1}; Table 4). Such similarity in the C-stocks for concave positions (soil depth 135 cm) investigated here could be explained by the fact that for the forest sites the sediment layers are smaller as compared to those of the today's grassland sites (Table 4). The thicker sediment layers at the grassland site were caused by erosion: Within the last 250 years approximately 63 Mg ha^{-1} of SOC (i.e., about 0.25 Mg ha^{-1} y^{-1}) is calculated to be transferred from convex into the concave positions (Frielinghaus et al., 1998 for a bulk density of 1500 kg m^{-3} and a SOC-concentration of 9 g kg^{-1} for the original topsoil).

The Eq. (1) according to Körschens (1980) is used to calculate an optimal SOC (SOC_{opt}) content for soils at convex positions depleted in SOC. Comparison of the calculated SOC_{opt} contents (8.4 g kg^{-1}) with those analysed for the soils at the convex positions (7.81 g kg^{-1}) suggested that the grassland soil could store a surplus of about 0.6 g kg^{-1} (Table 4).

3.2. Slope steepness and catenae position

For convex positions at the flat Prötzel catenae (CTII – Prötzel) the thickness of the Ap-horizon is found to be decreased by erosion (Fig. 3: soil profiles 3 and 4). Such truncation of soil profile should result in an admixture of sub- into the topsoil during ploughing. During truncation the content of organic C in the topsoil should decrease while the CO_3-C content should increase at the same time since the soil from deeper

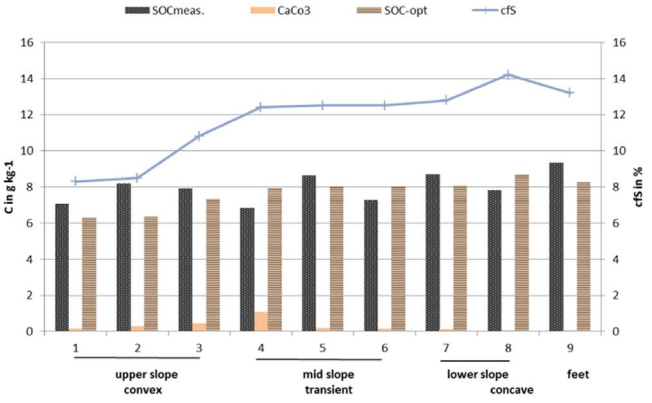

Fig. 3. Contents of soils organic carbon (SOC), fine sized particles (cfs, < 63 µm) and optimized SOC (SOC_{opt}) for a flat catenae (Type II) located at Prötzel site.

[1] cfs – particles < 0.0063 mm.

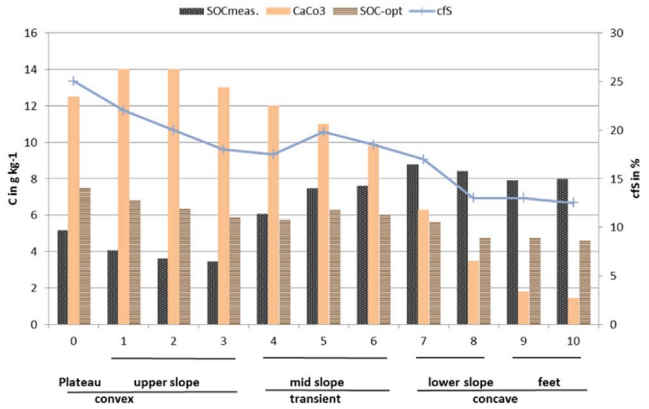

Fig. 4. Contents of soils organic carbon (SOC), fine sized particles (cfs, < 63 µm) and optimized SOC (SOC_{opt}) for a steep catenae (Type IV) at Holzendorf sit

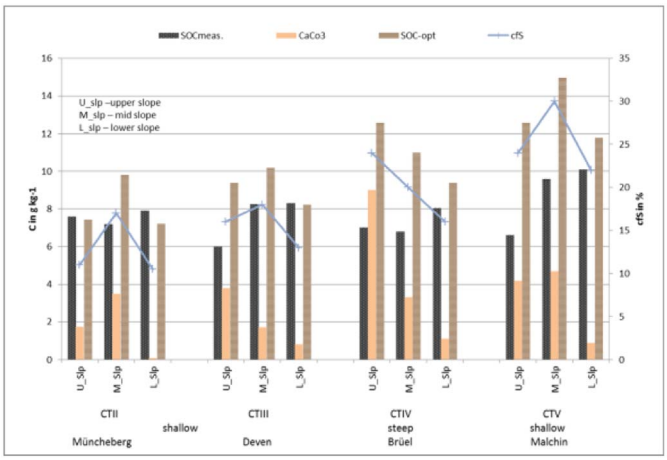

Fig. 5. Contents of soils organic carbon (SOC), fine sized particles (cfs, < 63 µm) and optimized SOC (SOCopt) for topsoils at catenae different in steepness located at Müncheberg, Deven, Brüel and Malchin site.

horizons is poor in SOC but rich in carbonate (Fig. 3). Despite this assumption the soils from Ap at the convex position of the Prötzel catenae show relatively low carbonate contents (0.29 g kg^{-1}). With a mean SOC-concentration of 8 g kg^{-1} of soil, the soils within this catenae can be assumed to be sufficiently supplied according to the site conditions (Körschens, 1997; Kundler et al., 1989). Comparing SOC contents of soils at convex with those at concave slope positions (6.8 to 9.2 g kg^{-1} soil) indicate for the soils at the convex position a SOC storage potential of about 2.4 g kg^{-1}.

The Holzendorf steep catenae (CTIV) (Fig. 1) at a loamy ground moraine show contrasting results (Fig. 4): the soils at convex and concave positions show stronger differences in SOC concentrations as compared to the ones of the Prötzel catenae (Fig. 3). The carbonate content in the Ap at the convex position is two to seven times higher as compared to that at the concave position caused by a relative stronger truncation of the soil profile as compared to Prötzel site. The transit positions between convex and concave positons are characterized by a slight decrease in carbonate and an increase in SOC-concentration (Fig. 4). The soils at the concave positions show the highest SOC-concentrations (8 to 8.8 g kg^{-1}) mainly due to sediment accumulation, segregation and a potentially higher plant growth. However, higher humidity will also increase microbiological activity which may result in long-term in a decomposition of organic material causing a decrease in SOC (e.g., UBA, 2016; van den Bygaart et al., 2007; van Oost et al., 2007).

Analyzing data of additional 125 top soils sampled within the young moraine region at various eroded arable sites revealed differences in SOC concentrations varying with slope and fine sized mineral particles (cfs) content. By using the cfs content to estimate the SOC concentrations according to Körschens (Körschens et al., 2014; Körschens, 1980) for 24% of the soils from convex (i.e., truncated soil profiles) the calculated data were found to be within the range of the analysed SOC concentrations (Fig. 5). For the soils from transition and concave positions about 23% and 30% of the calculated SOC data were found to be in the range of the analysed SOC concentrations. The recall ratio between the SOC data calculated according to Eq. (1) and the analysed SOC concentrations is between 23 and 30%.

3.3. Tillage and site conditions

In contrast to water erosion tillage erosion causes mostly short distance translocations (Kietzer, 2007). The net tillage erosion rates studied at the Müncheberg field experimental site decreased from tillage with a cultivator (4 Mg ha^{-1} y^{-1}), to ploughing (3 Mg ha^{-1} y^{-1}), to disk harrowing (1 Mg ha^{-1} y^{-1}). Attempting a ^{137}Cs-calculation with the mass balance model (MBM3) by Walling and He (1998) Kietzer (2007) found the shares of water to be higher than those of tillage erosion on CT II, III and IV (Table 5). Topography affects the extent of erosion and sedimentation rates caused by water and tillage erosion. For Basedow and Müncheberg, a mean change of -1 mm a^{-1} for convex and $+1$ mm a^{-1} for concave positions were found for tillage erosion (Table 5). For Holzendorf, -10 and $+10$ mm a^{-1}, respectively, were determined, while for Augustenfelde site the tillage erosion for the eroded slope was determined to be at least 0.1 mm a^{-1}. Assuming for the upper 1 mm of top soil a bulk density of 1.5 kg m^{-2}, and SOC concentrations of 7.8 g kg^{-1} for the eroded and 10.5 g kg^{-1} in the sedimentation areas, we calculated for the studied slopes SOC stocks of about 117 g m^{-2} for the convex and of about 157 g m^{-2} for the concave (deposition) areas which agrees with results found by van Muysen et al. (2006), van Oost et al. (2000), and Lobb et al. (1995).

3.4. Long-term tillage and crop rotation

Studies on field experiments at Dedelow (Table 2) suggested for the young moraine region a long-term averaged soil loss of 0.5 to 5 Mg ha^{-1} y^{-1} soil (Fig. 6) caused by erosion. Annual SOC translocations were between 7 g m^{-2} and 2015 g m^{-2} depending on crop rotation and erosion conditions (intensity/duration). For different crop rotations between 25 g m^{-2} (optimal soil cover), and about 360 g m^{-2} SOC (insufficient soil cover) were translocated from mid slope positions in average. A loss in soil thickness caused by erosion did not only affect soil fertility, it is also affects the SOC balance which is not always detectable by changes in the thickness of the Ap horizon. Further the erosion driven soil loss under fallow (Fig. 6) caused on average a decrease in soil thickness of 1 mm within 3 years (15 t ha^{-1} ≙1 mm soil ha^{-1}). The experimental data (Table 6) indicate high calcium carbonate content that offer -despite the negative effect of erosion on soil fertility- a potential to increase the soils capacity of SOC storage (e.g. Kögel-Knabner et al., 2008; Masiello et al., 2004; Torn et al., 1997).

At Holzendorf site (CTIV) selected steep plots were characterized by high levels of CO_3-C originating from the bed rock (i.e. glacial till) - that is mixed into the truncated Ap horizon. Fig. 7 shows typical changes in SOC-concentrations with the loss of soil. The SOC-concentrations of the sediments sampled during erosion events were between 3.2 and 21 g kg^{-1} (Fig. 7). Sampling during the years 2006 to 2016 at the ZALF-experimental site (Müncheberg) offers data on extreme erosion events and frequently occurring smaller erosion events. Such results could be used to calculate effects of erosion on SOC storage for example according to event (cascade and long-term for ZALF site) and site specific conditions. Recent studies at Müncheberg site - using a more detailed procedure focussing on the SOC analysis of cascaded samples obtained by time scheduled sampling (Deumlich et al., 2017) showed

Table 5
Difference of soil and carbon loss caused by tillage erosion and water erosion on four catenae types estimated with the mass balance model by Walling et al. (from Kietzer, 2007).

	Net-redistribution rate	Tillage		Water erosion		Tillage/water erosion		Soil translocation by tillage in		SOC loss[a]	SOC growth[a]
		Soil loss	Sedimentation	Soil loss	Sedimentation	Truncation by	Sedimentation by	Truncation area	Sedimentation area	Truncation area	Sedimentation area
	kg m^{-2} a^{-1}					Ratio		mm a^{-1}		g m^{-2} a^{-1}	
CTI Bas	− 6	− 14	9	− 6	5	2.3	1.8	− 1.1	1	− 12.9	15.8
CTII Mbg	− 26	− 10	4	− 25	3	0.4	1.3	− 0.7	0.9	− 8.2	14.2
CTIII Augf	− 7	− 1	0	− 7	0	0.1	0.0	− 0.1	0.1	− 1.2	1.6
CTIV Holz	− 76	− 55	59	− 80	1	0.7	59.0	− 9.1	9.8	− 106.5	154.4
	Redistribution: directed, by tillage erosion resulting of tillage operation										

[a] Calculated assuming 1 mm top soil thickness = 1.5 kg m^{-2}, SOC concentration of 7.8 g kg^{-1} in the truncation area and 10.5 g kg^{-1} in the sedimentation area.

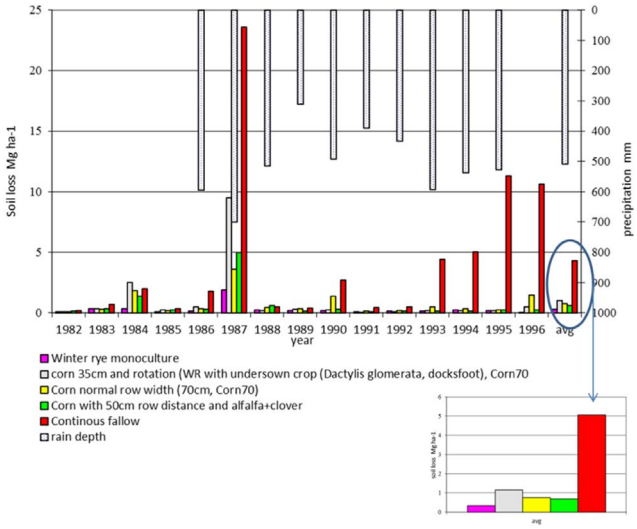
Soil loss Mg ha-1
precipitation mm
year
1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 avg
Winter rye monoculture
corn 35cm and rotation (WR with undersown crop (Dactylis glomerata, docksfoot), Corn70
Corn normal row width (70cm, Corn70)
Corn with 50cm row distance and alfalfa+clover
Continous fallow
rain depth

Fig. 6. Precipitation (mm a^{-1}) and soil loss (Mg ha^{-1}) for different soil management and crop rotations at a long-term field experiment at Holzendorf (K in Table 2) site for the years 1982 to 1996.

an enrichment ratio for SOC contents in the suspended sediments that is up to 10 times higher than that of sediments sampled by standard procedure (one collection tank, Table 7). Samples obtained by standard procedure offer mean SOC enrichment rates that depend strongly on the rainfall characteristics (intensity/amount) and runoff velocity: For low rainfall intensity the SOC enrichment could be about 2.5 but for higher intensities it may become < 1 (Deumlich and Barkusky, 2010).

4. Discussion

Analysis of neighbouring steep catenae in Burg Stargard (type IV) under forest and today's grassland (Frielinghaus and Ellerbrock, 2000) allows comparing erosion affected with none-erosion affected soils. In general the soils at the convex slope positions show lower SOC- and higher CO_3-C-contents as compared to the soils at the concave positions. The relative decrease in SOC content at the eroded slope positions compared to the none eroded positions were caused by dilution of the top soil material in the Ap horizon by admixture of soil material from the B horizon during soil tillage (Table 4).

Comparing SOC_{opt} contents (8.4 g kg^{-1}) calculated according to Körschens (1980) for the soils at convex positions with analysed SOC contents suggested a storage potential of about 0.6 g kg^{-1} (Table 4) for the grassland soils. The effect of land use on the SOC storage potential is found here to be much larger than the storage potential caused by erosion (+ 8%) since forest soils store in general SOC stocks that are about 30% higher than the ones stored in grassland soils (e.g., Blume et al., 2010; Leifeld and Kögel-Knabner, 2005; Thiere et al., 2005).

The difference between SOC_{opt} and analysed SOC contents (Figs. 3 and 4) are highest for soils at convex positions suggesting the theoretically available SOC storage potential not to be achieved. However, frequent erosion may cause a frequent truncation of topsoil at convex position such that optimal conditions for SOC storage at convex position will not be reached. More recently it is suggested that the soil organic matter in topsoils at eroded position is probably not in the same state of interaction with iron oxides as compared to that of non-eroded top soils caused by a continuous erosive loss of carbon (e.g., Berhe et al., 2007; Ellerbrock et al., 2016). The optimal storage at convex position seems to be limited by erosion driven translocation, however, the further downhill transport of the eroded material may force carbon storage at the concave positions.

The recall ratio between the SOC data calculated according to Eq. (1) and the analysed SOC concentrations indicate that erosion driven

Table 6
Difference of soil and carbon.

		Plot 8			Plot 11			Plot 15		
		Upper slope	Mid slope	Lower slope	Upper slope	Mid slope	Lower slope	Upper slope	Mid slope	Lower slope
%	cfs	21.7	22.4	18.3	21.7	23.8	21.6	22.6	24.4	24.4
g kg^{-1} soil	TC	15.20	11.75	10.95	16.75	16.55	13.65	19.70	20.00	18.10
	CO_3-C	7.60	4.45	2.95	8.23	8.35	5.90	12.60	12.45	9.45
	SOC	7.60	7.30	8.00	8.52	8.20	7.75	7.10	7.55	8.65
	SOC-opt	11.71	12.00	10.33	11.71	12.56	11.67	12.08	12.81	12.81
	SOC storage potential	4.11	4.70	2.33	3.19	4.36	3.92	4.98	5.26	4.16

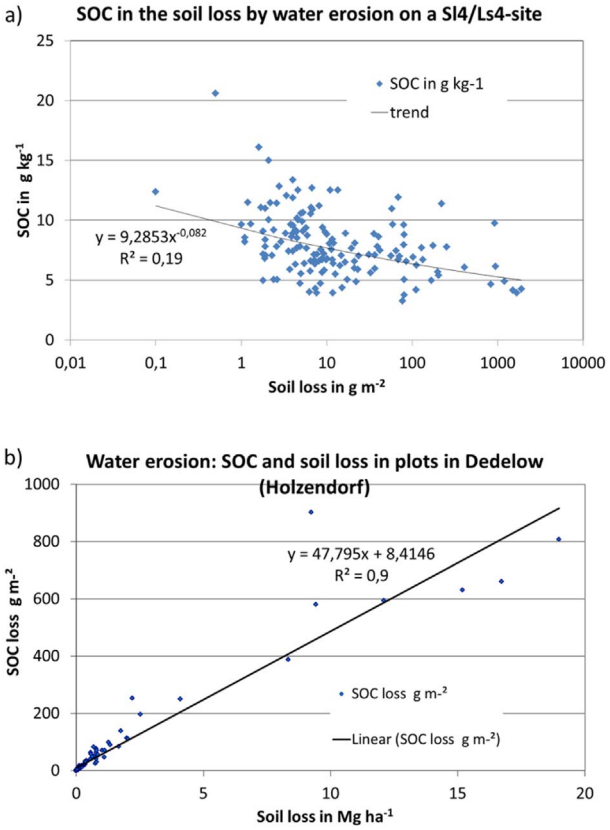
a)
SOC in the soil loss by water erosion on a Sl4/Ls4-site
SOC in g kg-1
trend
y = 9,2853x-0,082
R² = 0,19
SOC in g kg-1
Soil loss in g m-2
b)
Water erosion: SOC and soil loss in plots in Dedelow (Holzendorf)
y = 47,795x + 8,4146
R² = 0,9
SOC loss g m-2
Linear (SOC loss g m-2)
SOC loss g m-2
Soil loss in Mg ha-1

Fig. 7. a) SOC-concentration in sediments, and b) lateral C-flow estimated from soil loss multiplied by SOC concentration caused by water erosion at Holzendorf (K - in Table 2) site.

soil dislocations seem to affect SOC concentration by combining interactions between soil organic matter and (i) cfs particle content (Körschens, 2010, 1997), and (ii) cations such as iron (Berhe et al., 2007) or calcium (Tipping, 2005). Interactions between soil organic matter and cations are assumed to be closely related to the content of stable SOC (Bronick and Lal, 2005; Kleber et al., 2015), and to be affected by the specific composition of soil organic matter (e.g., Aquino et al., 2007). Such interactions may cause at different slope positions distinct ratios between respirable and stable SOC since the soil organic matter at convex and concave positions were probably not in the same state of interaction with iron oxides, for example (e.g., Ellerbrock et al., 2016).

Beside slope steepness and position the kind of soil management (crop rotation, soil cover, ploughing, no till etc.) also affect SOC losses due to erosion (Table 5). For a flat catenae at Müncheberg site (CTI) Li et al. (1999) found for a period of 15 years by using ^{137}Cs-distribution the magnitude of water erosion to be equivalent to that of tillage erosion. While Kietzer (2007) found the shares of water to be higher than those of tillage erosion (Table 5). These contrasting findings could be explained by the fact that the study of Li et al. (1999) consider a time span with mostly lower rain erosivity. At this site tillage and water erosion seems to be intimately linked such that a differentiation becomes complicated. However, there is in general a lack in distinguishing between short and long term SOC storage (Roeckner et al., 2011).

In any case for rainfall intensities above 15 mm h^{-1} erosion is observed (Deumlich, 1999). Smaller water erosion events (< 7.5 mm or < 5 mm h^{-1}, Frielinghaus et al., 2002) can mostly be disregarded with respect to soil loss. Lower rainfall intensity will cause lower velocity and lower transfer rates, resulting in a preference for the transport of smaller sized particles, which in turn have a higher nutrient concentration (Hjulström, 1935; van Hemelryck et al., 2010). Note, eroded small sized particles (< 63 µm) were often transported over long-distances into river systems finally causing an overall loss in soil fertility for the eroded sites (Doetterl et al., 2016). Since smaller erosion events occur frequently they could become most important for SOC transfer over short distances.

Since the amount of material suspended in runoff will decrease with rainfall intensity and flow velocity (Hjulström, 1935) low rainfall intensity will mainly cause transfer of dissolved organic matter. Thus, for the sites investigated here, mostly organic matter soluble in water will be lost from convex positions during frequently occurring smaller erosion events. Since water soluble organic matter is assumed to present an easily decomposable fraction (Ellerbrock and Kaiser, 2005) erosion driven changes in SOC stocks would almost exclusively be related to a loss in decomposable carbon pools. To improve the prediction of SOC loss from croplands the sampling of sediment, and runoff, the latter separated into suspended and dissolved fractions, need to be sampled

Table 7
Comparison of SOC and cfs-contents of plot soil and sediments in the cascade equipment.

Date 29/05/2007	Plot 2				Plot 1			
	g kg^{-1} SOC	ER[a]-SOC	cfs %	ER-cfs	g kg^{-1} SOC	ER-SOC	cfs %	ER-cfs
Plot	5.60		6		6.91		5	
Barrier + V-channel	2.60	0.46	3	0.55	10.40	1.51	4	0.72
Bottles in collector	60.05	10.72	53	9.42	69.73	10.09	52	9.99
Soil loss g m^{-2}	154				24			

[a] ER-enrichment ratio.

Fig. 8. Ephemeral gully in an arable field.

with respect to the changing conditions during the erosion event.

During extreme erosion events soil losses exceeded strongly the mean values of SOC transfer (Deumlich, 2012) discussed above: In the year 2007 the maximum rain intensities arrives 1.95 mm min^{-1} (per 1-min interval), 1.72 mm min^{-1} (per 10-min interval) and 1.71 mm min^{-1} (per 30 min interval) during one rainstorm with about 400 N h^{-1} (148 mm of rainfall) (Vogel et al., 2016). This rainstorm caused at a corn-field located near the long-term Dedelow field experimental site a mean soil loss of about 780 Mg ha^{-1} y^{-1} which is equivalent to a loss of about 50 mm in the thickness of the top soil. By using data obtained for Holzendorf site (Figs. 6, 7) a SOC-loss of about 5 to 7 Mg ha^{-1} y^{-1} for this extreme event was calculated (Vogel et al., 2016). Note, such losses are mostly limited to regions of gullies formed during extreme erosion events (Fig. 8). Such results indicate that for estimating effects of erosion on carbon budgets exact measurements of soil and carbon translocation in standardised plots are required.

5. Conclusion

For understanding of landscape-scale SOC dynamics in arable soils the erosion effects on SOC dynamics were found to be important. Re-evaluating results of earlier investigations originally focussing on developing of erosion protection measures based on the relation between SOC and cfs contents indicate a higher SOC storage potential for soils at concave positions as compared to the ones at convex positions. Site specific contents of fine sized (< 63 µm) mineral particles (cfs) could be used to explain the SOC contents of 23 to 33% of the top soils from 125 soil profiles located at sites different in slope steepness and position. The recall ratios between 23 and 30% indicate that additional processes like the interaction between soil organic matter and cations (e.g., iron, calcium) seem to be relevant for the SOC storage potential. For eroded soils the difference between real SOC and SOC_{opt} (i.e., calculated from the cfs content) indicated that such soils could potentially store a surplus of 0.6 to 0.8 g kg^{-1}, which is about five to twenty times smaller than the surplus that could be stored via tillage (soil cover) or re-forestation. However, downhill transfer from convex towards concave positions will prevent a continuing SOC storage within soils at convex positions such that an achievement of optimal SOC storage at this position could not be assumed.

For the soils investigated here the SOC storage capacity was strongly limited by the small clay and silt contents, and frequent truncation of the soil profiles at convex positions. The loss of small amounts of soils by frequent erosion events seems not to be of relevance in terms of soil fertility; however, the amount of translocated SOC may become relevant with respect to deposition, if site conditions prevent SOC from decomposition. Especially extreme rainstorms may increase strongly the amounts of SOC buried deeply at concave positions. In consequence SOC storage may take place via the deposition of translocated material to concave sites (depression) where the SOC may be buried within deeper horizons. Thus, re-evaluation of former studies, together with recent findings and up to date techniques may improve our understanding on influences of soil erosion in context of SOC storage and climate change.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at https://doi.org/10.1016/j.catena.2017.11.016. These data include the google map of the most important areas described in this article.

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